AOARD REPORT

Visit to Ionospheric Modeling and Remote Sensing Branch,
Phillips Laboratory in Hanscom AFB, MA

2, Nov 1994
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With financial support provided under the AFOSR sponsored Window-on-Science program, Dr Gary Tuck of the University of Queensland, Australia spent a two week tour at Ionospheric Modeling and Remote Sensing Branch, Phillips Laboratory in Hanscom AFB, MA for the purpose of carrying out preliminary discussions with Phillips Lab's gravity group personnel on use of the terrain correction methods. The report provides a scope of Dr Tuck's research in which he is intended to work together with Phillips lab personnel during his continuing stay at Phillips laboratory this year and part of the next year. The two research areas discussed by Dr Tuck in this report are 1) detailed gravimetric surveying to locate underground structures and 2) the use of air-born gravity gradiometry to avoid oncoming terrain.

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Contract Period: 10 Sept 94 through 1 Oct 94

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Summary:

Preliminary discussions with the gravity group at the Phillips Laboratory concentrated on the details of the terrain correction methods that they used for the TV tower experiments in North Carolina in 1988 and Mississippi in 1991. Their methods were compared with the technique that the Australian group developed for terrain corrections at the mine in northwest Queensland based on the topography being represented by triangular prisms that use the survey points as apexes. Although using the same principle the groups developed slightly different methods because the topography around the TV towers was less steep than that around the mine. For this reason terrain corrections around the TV towers using the Australian method will be a routine calculation, that is manageable CPU time, and it will be the first task once my programs are successfully relocated on to a Phillips laboratory computing platform.

Two projects, related to gravity gradiometry, that have recently assumed high priority with thegroup at the Phillips laboratory are 1) Detailed gravimetric surveying to locate underground structures and 2) The use of air-borne gravity gradiometry to avoid oncoming, terrain. (Another project, which was one of the principal reasons for visiting the laboratory and in which I hope to collaborate is the

balloon GPS/IMU experiment that was scheduled to occur in the latter part of 94. Because of problems with the gyroscopes and accelerometers of the IMU unit from a particular company another supplier had to be organized and a test of their equipment undertaken. This has now occurred but the balloon launch has been delayed by about 6 months.) The former project proposes the use of detailed high resolution gravity and or gravity gradiometry observations to locate underground excavations or buried objects. It is anticipated that topographic effects, while present, will play a minor role in the reduction of the gravimetric observations. Because of the small areal extent of the observations there appears to be no computational advantage in representing the topography with triangles rather than grided topographic data. Grided observations are likely because topography data would coincide with gravimetric observations that are undertaken along a series of traverses normal to the long axis of an underground object. The latter project requires a detailed knowledge of terrain effects particularly topography of high relief. Thus representation of the terrain with triangles would appear to be an advantage.

However for reasons discussed later gravimetric observations have to follow a grided pattern so the use of triangular prisms will have to be assessed.

The programs that were developed for terrain corrections around the mine were coded in C and run on an Apollo 10000 which was a relatively fast machine. The programs of the group at the Phillips Laboratory were in Fortran and run on a VAX 7000 which appears comparable to the Apollo in CPU speed.

Introduction.

In the past decade terrain corrections have played a crucial role in geophysical tests that have examined a breakdown in Newton's inverse square law of gravity. These geophysical observations in mines, lakes and on tall TV towers were members of a large group of experiments [1-6] that examined non-Newtonian gravity; popularly referred to as the "fifth force".

While early results from tower experiments by Eckhardt et al. [7] and Thomas et al. [8] in the United States and a mine experiment by Stacey et al. [9-11] in Australia indicated a breakdown in Newtonian gravity further detailed examination of the effects of the topography following comments by Bartlett [12] and Jekeli [13] removed most of the discrepancy with Newtonian gravity [14]. Topography surrounding the towers in North Carolina and Nevada in the USA was flat relative to that around the mine at Mount Isa in Queensland, Australia so the techniques developed to determine the terrain corrections differed slightly. For the tower experiment of Thomas et al., the topography was covered by concentric circles with radial lines dividing circular annuli and the average elevation was determined for each sector. Eckhardt et al. represented the topography with digital elevation data out to 10 km from the base of the tower which were sorted into triangles that were then used to obtain elevations at the comers of 50 m grids. The method used for the mine experiment was to represent the topography with digital topographic data increasing, the density of the data in areas of high relief and close to the mine. The data was then sorted into optimized triangles and the terrain corrections were obtained at the surface and down the mine shaft for the gravitational attraction of triangular prisms that used the survey points as apexes. The distinct advantage of this method is that it removes the bias inherent in conventional gravity surveying. It is now recognized that topographic data obtained from gravity surveying is biased because inaccessible areas are inadequately surveyed [15].

The method used by Eckhardt for terrain corrections appears simpler than ours because graded data enables the expression for the gravitational attraction of a right-rectangular prism to be applied with the consequent reduction in computational time. The sorting program to produce optimized triangles was a subroutine of a plotting program on the VAX. This program will be used on the Mount Isa gravity data and the results compared with ours.

My programs have now been transferred to a computing platform at the laboratory that operates in UNIX (System V Release 4) and has a C compiler.

Scope of Research:

Terrain corrections are one of the routine reductions that are applied to exploration gravity data. According to the objective of the survey, elevations obtained from gravity observations may suffice for terrain corrections. However if detailed terrain corrections are required gravity data must be supplemented with cartographic data and several methods of processing topographic observations have evolved. Traditionally the method used for exploration surveys is the adaptive graded scheme developed by Hammer [16]. A zone-chart consisting of a series of concentric circles with radial lines dividing the area between concentric radii into sectors is constructed on transparent sheeting and placed over a gravity station. The size of each sector is adjusted according to the effect that it would have on the gravity station. If elevations from gravity stations are inadequate independent topographic data are added. Data are derived from contour maps that are manually scanned to determine the average elevation of a sector; a task of increasing complexity when the topography is steep. It is now widely recognized that terrain corrections based on gravity surveys are biased since the observations are generally made at positions of convenience. Even zone-chart calculations may be biased if areas are not properly scanned. The results for terrain corrections for the topography around the TV towers and the mine were subsequently shown to contain a bias in the terrain calculations due to inadequate representation of the topography.

Since the development of portable and accurate relative gravity meters in the late 1940's the time consuming and expensive section of gravity surveying has been the collection of accurate coordinates of the gravity stations, particular elevation. This deficiency is being overcome with improved instrumentation and techniques such as the Global Positioning, System (GPS) but it is likely to exist until the end of the decade. Now with the availability of increasing digital topographic data from government sources and improved computing capabilities there is a need for improved automated methods of processing data that also lead to an increase in precision. Several methods have been reported and some are more convenient than others. The accuracy of each method of calculating terrain corrections however depends on the accuracy of the digital data and that question has been examined in detail [15]. Contour maps are produced from aerial photographs that are examined stereoscopically and land surveying data and are generally only accurate to one half a contour interval. Digital data is obtained as a list of coordinates along specified contours and thus the elevation component of the data begs the question of its accuracy. Eventually topographic maps will be replaced by ones with contours accurate to several centimeters as improved space-borne instrumentation for probing the earth's surface is launched.

The most convenient technique for determining terrain corrections for mass above a reference surface is to use graded data since the expression for the gravitational attraction for a right-rectangular prism can easily be applied. However it is not always possible or desirable to obtain gravity observations in this form. By using surveying points as apexes of right-triangular prisms our approach combines the topographic information from both the gravity survey and a cartographic database for the survey region, to produce a triangular mesh which models the terrain more effectively, especially in areas of large relief and in the proximity of each gravity station, where the data are sensitive to terrain corrections. Such a procedure allows additional data prepared by hand-digitizing contours to be included. Very large data bases may be generated so it is essential that automated methods are developed to accommodate them.

In our technique each digital topographic data point is assigned a value for easting, northing and elevation. The first step is to identify the point with the smallest value of easting; this is labeled the origin. A heap sort [17] is then applied to order and number the points according to their (square) Euclidean distance from the origin. The next step is to arrange the points into triangles of optimum shape. The triangulation is based on the method reported by Lawson [18] which is a technique that maximizes the minimum internal angle of a triangle according to certain criteria. The program tests each new triangle as it is formed and the vertices of the triangle are stored in a counter-clockwise order. The required triangle was determined by searching backwards through the list of triangles, because the more recent triangles at the end of the list are the ones that were formed from the latest grouping of points. A forward search was found to reduce the algorithm's efficiency to the order of n^2, rather than $n^{4/3}$. Once all points have been assigned to triangles the structure is saved as a list of the vertices of each triangle. In order to calculate a terrain correction using a triangular mesh we developed an expression for the gravitational attraction due to a right-rectangular prism based on the volume integral which is the method used by several authors. Analytical expressions derived from the volume integral are easily derived for right-rectangular prisms [19] but this technique is not suitable for representing complex bodies. By appealing to the divergence theorem others [20-22] have used a surface integral to determine the contribution of a polyhedron composed of triangular facets that are used to represent a complex body. Paul's method however was restricted to external points and required a cumbersome procedure to determine the contribution of each facet. Barnett also represented the solution for a polyhedral body that was valid for external and internal points but the directional angle relative to the normal to a triangular face is not well described and rather confusing coordinate transformations were used. An analytical solution for the gravitational attraction of a right-triangular prism with either a flat top or a sloping top was reported by Okabe for interior, surface and external points. However his solution introduces singularities that must be examined. Our analytic solution for a flat-top prism, similar to the method used by Okabe, gives the gravitational attraction at any point, has no singularities and is computationally fast. For sloping top prisms the upper surface is taken to be the average of the heights of the three vertices.

In summary the approach of using a triangular mesh has several advantages:

1. it models the terrain more effectively than other methods, especially in areas of high relief,
2. accommodates large amounts of topographic data, and
3. provides a significant increase in precision.

Discussion and Comment:

The area of interest to the croup at the Phillips laboratory that were proposed in the AOARD application were

- o discussion of the development and advantages of the terrain correction method using triangular prisms to represent the topography
- o examine the possibility of different ways of sectoring the computer program to speed up the calculation process for each gravity station
- o discuss the latest techniques for upward and downward continuation of gravity observations (if there is time).

It was mentioned in the introduction that the group at the laboratory used a program to produce optimized triangles from digitized topographic data. The program, TRILATE, is a subroutine of a program CONTNG from the NCAR library on the VAX computer. It seems similar to the heap sort and triangulation one that we developed as it is based on the max-min-angle criterion used by Lawson [18]. Details of the library program will be obtained and it will be tested on the data for the Mount Isa mine.

Topographic data for the two TV towers will be analyzed with my programs and results for terrain corrections at the bases of the towers and the gravity stations will be compared to the published results. Using the gravity data for the TV towers a comparison will also be made between the two sorting and triangulation methods.

For most large data sets the calculations of the effect of the topography at each gravity station requires significant computational time. Other approaches for reducing, computational time will be examined.

Preliminary discussions with D. Gleason on the methods of upward continuation of gravity data at the mine in Australia suggest that the highly efficient Fast Fourier Transform technique could be used to determine gravity or the gravity gradient at elevations above the surface. However an initial assessment is that this method requires reduction of the raw data in order for it to be in a grided form that is necessary for the FFT process. Gravity data would need to be interpolated to provide graded values. Because the inverted results are required at high precision (i.e. the order of microgals) the interpolation procedure would compromise the accuracy of the method. Alternatively the normal continuation method, based on Fourier analyses of both gravity and topographic data, will be used. Its advantage is that the data sets from the same area can be independent, although it is necessary to know the elevation of each gravity data point. Upward and downward continued gravity may then be calculated at any point from the Fourier coefficients. The use of the FFT technique will be further examined.

Conclusion:

The outcome of the discussions, which included a seminar on my research, during this visit is likely to be an improved understanding of the details of each groups technique for terrain calculations. Sharing of high resolution topographic data that is normally not available will allow further research of the type outlined in this report to occur.

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